DEVELOPMENT OF A LOW CHARGE-TO-MASS RATIO POST-ACCELERATOR FOR THE RIA PROJECT

P.N. Ostroumov, J. Nolen, R.C. Pardo, K.W. Shepard
Physics Division, Argonne National Laboratory

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ABSTRACT

A post-accelerator for rare isotopes (RIB linac) which must produce high-quality beams of radioactive ions over the full mass range, including uranium, at energies 10 MeV/u or higher. To provide the highest possible intensities of rare isotopes with masses from 6 to 240, the linac will accept all ions starting from the 1+ charge state. A high resolution separator for purifying beams at the isobaric level precedes the RIB linac. Charge stripping in the linac takes place at two stages: helium gas stripping at energies of a few tens of keV/u, and an additional foil stripping at ~1.1 MeV/u for the heavier ions. The RIB linac will utilize existing superconducting heavy-ion linac technology for all but one exceptional piece, a very-low-charge-state injector, which is needed for the first ~10 MV of the accelerator. This section consists of a pre-buncher followed by three sections of CW, normally-conducting RFQs. We report on the present status of the RIB linac development and plans for the future R&D effort.

LAYOUT OF THE POST ACCELERATOR

An initial concept of the RIA post accelerator suitable for ions up to mass 132 has been described in ref. [1]. This paper presents a modified design of the RIB linac which must produce high-quality beams of radioactive ions over the full mass range, including uranium, at energies above the Coulomb barrier, and have high transmission and efficiency. The design of the RIB linac presented below can accelerate uranium ions up to 10 MeV/u and lighter ions up to 20 MeV/u.

The most efficient generation of rare isotope beams requires singly-charged ions at initial injection. Very-low-charge-state ions can most efficiently be bunched and accelerated by using several sections of cw, normally-conducting RFQ for the first few MV of the RIB accelerator [2]. A high resolution state-of-the-art separator for purifying beams at the isobaric level precedes the RIB linac [3]. The mass filtering process will provide high purity beams while preserving transmission.

For best efficiency over the full mass range, helium gas stripping must be performed at different energies for different mass ions. The linac following this stripping can accelerate ions of charge to mass ratio 1/66 and above. For example, by stripping at 7 keV/u, some 55% of an incident ^{132}Sn beam can be stripped into a charge state 2+ and further accelerated [4]. For the heavier ions of Z>54, higher charge states are required, for which the best stripping efficiency is achieved at the higher energy of 20 keV/u.

The block-diagram of the RIB linac is shown in Fig. 1. It consists of the following main sections [5]:

- A high-resolution isobar separator.

- An injector with three sections of normally-conducting RFQs.
- A superconducting linac which will accelerate ions of q/m > 1/66 to 1.1 MeV/u or more.
- A carbon-foil stripper at beam kinetic energy per nucleon $W_n \geq 1.1$ MeV/u, when necessary, to provide a q/A≥35/238 for the last stage of acceleration. The beam energy at this point depends on the particular charge-to-mass ratio.
- A superconducting linac to accelerate ions of q/A≥35/238 to energies of 10 MeV/u or higher.

To meet multi-user capability the RIB linac will be supplied by the charge breeder that can inject beams directly into the existing positive ion injector (PII) and then to the section 11 of the linac as is shown in Fig. 1. At this mode the low energy beams from the sections 7 and 10 will be simultaneously directed to the astrophysics experiments.

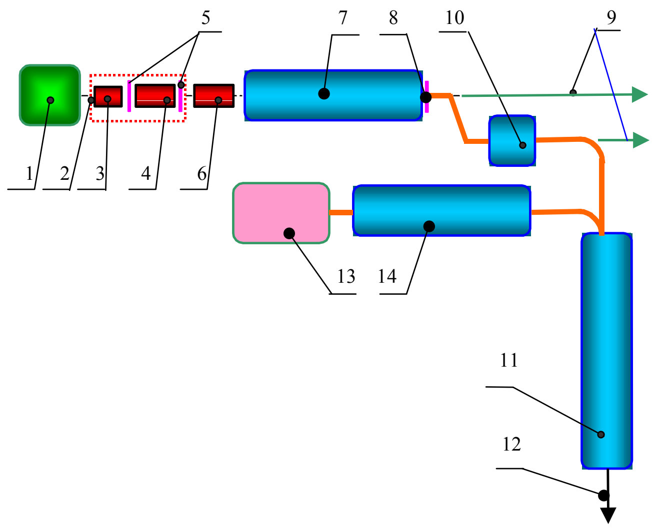

Figure 1. Block-diagram of the RIB Linac. 1 – Isobar separator, 2 – High voltage platform, 3 - 12 MHz RFQ, 4 – 12 MHz Hybrid RFQ, 5 – helium strippers, 6 - 24 MHz Hybrid RFQ, 7 – SC Linac between the strippers, 8 – carbon stripper, 9 – beams to astrophysics experiments, 10 – SC booster linac, 11 – upgraded ATLAS, 12 – high energy beams, 13 – charge breeder, 14 – positive ion injector (section of ATLAS).

INJECTOR SECTION

The buncher, conventional 12-MHz RFQ and hybrid-RFQ sections, and both He-gas-stripper cells will be placed on a −380 kV open-air variable-voltage platform. Placing these elements on a variable-voltage platform allows operation with a fixed constant-velocity profile for the full mass range of ions, including uranium. The 12-MHz gridless, four-harmonic bunching system can bunch approximately 80% of a dc beam into 1 nsec bunches, forming excellent longitudinal emittance. The RFQ should operate at as low a frequency as is practicable to maximize the transverse focusing strength. As it has been demonstrated at ANL the split-coaxial RFQ geometry is appropriate for operation at 12

MHz [5]. The RFQ is designed for a minimum charge to mass ratio of 1/240: ions of higher charge state are accommodated by simply scaling both the platform voltage and the RFQ rf voltage to match. The cw vane voltage of 92 kV with a mean bore radius of 9 mm has been proven entirely practical in extensive tests of the prototype 12-MHz RFQ at ANL. Numerical simulations of the beam dynamics through the MHB and RFQ sections have been performed. Two electrostatic quadrupole triplets are used for beam matching between the buncher and RFQ. The proposed design achieves longitudinal emittance as low as 0.2 π·keV/u-nsec for 80% of cw beam entering the buncher.

Table 1. Accelerating elements of the RIB linac.

Section	Geometrical beta, β_G	Maximum A/q	Frequency (MHz)	Number of Elements	Section Voltage (MV)
RFQ	-	240	12.125	1	1.23
H-RFQ-1	-	240	12.125	1	3.16
H-RFQ-2	-	66	24.25	1	2.86
SC	0.0172	66	48.5	12	10.8
SC	0.026	66	48.5	16	22.1
SC	0.0389	66	72.75	30	43.2
SC	0.0763	238/35	72.75	6	6.7
SC	0.065	238/35	97.0	12	8.5
SC	0.105	238/35	97.0	24	25.7
SC	0.141	238/35	109.125	16	24.6

Hybrid RFQ

High-efficient acceleration of well bunched ion beams will be performed in the proposed hybrid RFQ (H-RFQ) structure [7]. We found that the concept of separated accelerating and focusing zones can be applied to the acceleration of heavy ions with $q/A \geq 1/240$ and at very low energies if the beam focusing is provided by rf quadrupoles.

The beam dynamics design of the H-RFQ structure was performed in two steps: 1) preliminary design of the longitudinal layout and 2) detailed simulation of beam dynamics in 3D electric fields. These steps were iteratively repeated in order to achieve design goals: minimal emittance growth, lowest possible peak surface field, lowest sensitivity to the misalignments and rf field errors, and maximum possible 6D acceptance. The first DT section of the H-RFQ operates at zero synchronous phase while the last two DT sections operate at –20° synchronous phase. The 1+ rare isotope beams come from either standard ISOL-type ion sources or a helium gas catcher and, therefore, the maximum expected transverse normalized emittance is quite low, ~0.1 π·mm-mrad. Heavy beams such as uranium will be formed with even lower normalized emittances, ~0.01 π·mm-mrad.

Several resonant structures have been considered as candidates for the H-RFQ. We have chosen a design based on four strong coupled quarter-wave resonators. To determine complete engineering specifications, an aluminum 1:2 model of the H-RFQ for the RIA RIB linac was built and tested [8].

Another H-RFQ operating at 24.25 MHz will be designed for acceleration of ions with lowest charge-to-mass ratio 1/66 in the energy range from 20 keV/u to 62 keV/u. Numerical simulations of the beam dynamics through the entire chain of RFQ sections have been performed. A preliminary study using linear codes shows that beam matching between the RFQ sections, including stripping, is straightforward, and can be achieved without any emittance growth in either the transverse or the longitudinal phase plane. Several rf bunchers are required for the matching purpose. Transverse focusing in the transitions can be done with electrostatic quadrupoles.

SUPERCONDUCTING LINAC

The low-charge-state injector linac can be based on established interdigital drift-tube SC niobium cavity designs, which can provide typically 1 MV of accelerating potential per cavity in this velocity range [1]. The low-charge-state beams, however, require stronger transverse focusing than used in existing SC ion linacs. For the charge states considered here (q/A = 1/66) the proper focusing can be reached with the help of strong SC solenoid lenses with fields up to 15 T. Commercial vendors now offer a wide range of high field magnets in the range of 10 to 17 Tesla.

The SRF linac consists of 56 interdigital four-gap cavities operating at -20° synchronous phase, and each cavity is followed by a SC solenoid. This linac can accelerate any beam with $q/A \geq 1/66$ over the velocity range $0.0011 \geq \beta \geq 0.05$.

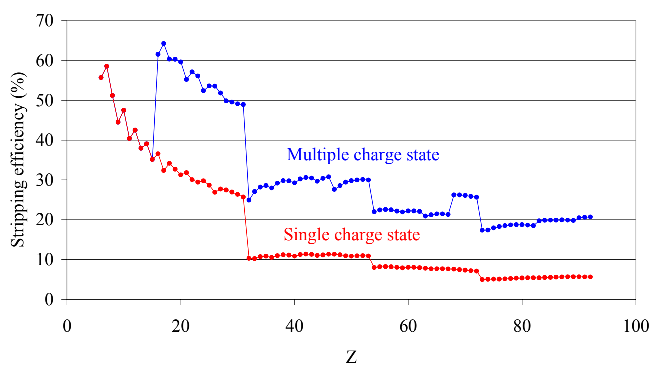

Figure 2. RIB linac overall stripping efficiency in the regime of single and multiple charge state beam acceleration.

After the second stripper, the desired charge state must be selected and further accelerated to the beam velocity required to match to the ATLAS linac section in order to provide the last stage of acceleration to the desired beam energy. The post-stripper section of the RIB linac will be designed for the acceleration of multiple-charge-state beams to enhance the available beam intensities for experiments. As it was shown in [9] a wide range of the charge spread $\Delta q/q$, about 20%, can be accepted and accelerated in the ATLAS accelerator. We have restricted the possible range of $\Delta q/q$ to ≤11% in order to avoid emittance halo in the phase space. Depending on the ion mass number a range of charge states from 2 to 4 can be accepted for acceleration. As a consequence of multiple-charge-state acceleration the total stripping efficiency is significantly higher than for the single charge-state beams, as can be seen in Fig. 2. The RIB linac of the RIA Facility will

produce beam intensities an order of magnitude higher as compared with post-accelerators based on an ECR charge breeder. However, the transverse and longitudinal emittances of multi-q beams will be larger by a factor of ~3 as it follows from beam measurements in ATLAS [9].

Further acceleration by six SRF cavities of β_G=0.0763 is required in order to bring the beam energy to approximately 1.4 MeV/u and match the velocity acceptance of the β_G =0.065 resonators in ATLAS. The present ATLAS configuration is being enhanced by adding new SC cavities.

CONCLUSION

Low charge-to-mass ratio post-accelerator is technically feasible. RIA post-accelerator will have high acceleration efficiency for all masses. The following future R&D work is needed:

1) Prototyping of 12 MHz Hybrid RFQ. Testing with full level of rf power, testing with beam for q/A=1/132.
2) Prototyping of 4-gap SC resonators to demonstrate E_{peak}=20 MV/m.
3) Prototyping of 15 Tesla solenoids together with a SC resonator.
4) Study the properties of high-resolution isobar-separator in terms of tolerances and technical feasibility.
5) Study beam dynamics options for focusing of low q/A heavy-ion beams.

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